Dynamic Search Space Squeezing Technique for Large Scale Optimal Load Dispatch

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This paper presents a new approach to the solution of optimal power generation for economic load dispatch (ELD) using dynamic search space squeezing strategy to particle swarm optimization (PSO) technique. In this paper an Improved PSO (IPSO) technique is suggested that deals with an inequality constraint treatment mechanism called dynamic search space squeezing strategy to accelerate the optimization process and simultaneously the inherent basics of conventional PSO algorithm are preserved. The algorithm uses payoff information for finding feasible near global solutions to evaluate optimal generation. The proposed method easily takes care of transmission loss, dynamic operation constraints (ramp rate limits) and prohibited operating zones and also accounts the non-smoothness of cost function arising valve point loadings. To verify the robustness and superiority of the proposed IPSO with one smooth and other non-smooth cost function with valve point loading effects is applied in ELD problems. The simulation results reveal that the proposed IPSO ensures convergence within an acceptable execution time and provides highly optimal solution as compared to the results of conventional numerical methods, Tabu search method, evolutionary programming approaches, genetic algorithm, modified Hopfield neural network, modified PSO and artificial immune system (AIS) approaches reported in literature.

Keywords : AIS; PSO; Prohibited operating zone; Ramp rate; Valve point effect

NOTATION

a_i, b_i and c_i	:	fuel cost coefficients of i^{th} generating unit
B_{ij}	:	loss coefficients
c_1 and c_2	:	acceleration constant
e_i, f_i	:	constants of i^{th} unit with valve point effects
F	:	total cost function of the system
i	:	number of generators in a particle
$iter$	:	the current number of iterations
$iter_{max}$	:	the maximum number of iterations (generations)
j	:	number of particles in a group
K	:	constriction factor
k	:	pointer of iterations (generations)
m	:	total number of committed online generators
P_D	:	total system load demand
P_i and P_i^0	:	current and previous power output of i^{th} generator, respectively
$P_{i\,min}$, $P_{i\,max}$	:	minimum and maximum limit of real power output of i^{th} generator
P_{iL}^{pzk} and P_{iU}^{pzk}	:	lower and upper limits of k^{th} prohibited zone for generating unit
P_{loss}	:	transmission network loss
R and ()	:	random number in the range [0,1]
U_{ri} and D_{ri}	:	up ramps and down ramp limits of the generator
w	:	inertia weight factor

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INTRODUCTION

The main objective of economic load dispatch (ELD) of electric power generation is to schedule the committed generating unit outputs so as to accomplish the load demand at minimum operating cost, while satisfying all unit and system equality and inequality constraints. This makes the ELD problem a large-scale highly constrained nonlinear optimization problem. Because of its non-linear characteristics with heavy equality and inequality constraints that make the problem of finding the global optimum difficult using any mathematical programming and optimization techniques. Usually, the ELD problem is a sub problem of unit commitment and a constrained optimization one. Over the years, various mathematical methods and optimization techniques have successfully been employed to solve for ELD problems. The conventional methods include lambda iteration method[1], base point and participation factor method, gradient search method, etc. These numerical methods require the incremental cost curves to be monotonically increasing or piecewise linear. However these methods have difficulties and are not suitable to address non-linear and discontinuous characteristics of actual practical problems[2]. A dynamic programming method (DP) can solve such problems in different formulations. However, this method suffers from massive computational efforts for its large dimensionality when applied to practical size ELD problems in stipulated time frames.

In the past decades, stochastic search algorithms like simulated annealing (SA)[3], genetic algorithm[4-6] and evolutionary programming may prove to be very efficient in solving complex power system problems but these heuristic methods do not always guarantee the globally optimal solution. In recent years, particle swarm optimization (PSO)[7–15] and artificial immune systems (AIS) have successfully been applied to ELD problems[16]. Quite promising results in terms of fuel cost savings have been reached by these techniques.

To show its efficiency and effectiveness the IPSO methodology is applied to constrained quadratic cost functions with generator constraints, power loss, ramp rate limits and prohibited operating zones. The IPSO is tested on six generators and 40 - generators with valve point loading effects. The results so obtained show its capability and superiority in solving ELD problems.

PROBLEM DESCRIPTION

ELD problem is about minimizing the fuel cost of generating units for a specified period of operation so as to accomplish optimal dispatch among the committed units and in return satisfying the system constraints. Here, two models for ELD are considered, namely, one with smooth cost function and the other with non-smooth cost function as detailed here.

Case A : ELD Problem with Smooth Cost Function

The prime objective of the ELD problem is to determine the most economic loadings of generators to minimize the generation cost such that the load demands in the intervals of the generation scheduling horizon can be met and simultaneously all the equality and inequality constraints are satisfied.

Here the constrained optimization problem

$$\text{Minimize } F = \sum_{i=1}^{m} f_i(P_i) \quad (1)$$

In general, the cost function of i^{th} unit $f_i(P_i)$ is a quadratic polynomial expressed as

$$f_i(P_i) = a_i + b_i P_i + c_i P_i^2 \text{ (\$/h)} \quad (2)$$

This constrained ELD problem is subjected to a variety of constraints depending upon assumptions and practical implications like power balance constraints, generator output constraints, ramp rate limits and prohibited operating zones.

Power Balance Constraints

This constraint is based on the principle that the total generation $\sum_{i=1}^{m}(P_i)$ should be equal to the total system demand P_D plus the network transmission loss P_{Loss}, which is represented by

$$\sum_{i=1}^{m}(P_i) = P_D + P_{Loss} \quad (3)$$

To calculate the transmission losses, B coefficients method is used in general.

The loss is represented by B coefficients.

$$P_{Loss} = \sum_{i=1}^{m}\sum_{j=1}^{m} P_i B_{ij} P_j + \sum_{i=1}^{m} B_{0i} P_i + B_{00} \quad (4)$$

The B-coefficients are based on the generation in per unit.

The Generator Constraints

The generation output of each unit should be between its minimum and maximum limits. That is, the following inequality constraint for each generator should be satisfied by

$$P_{i\min} \le P_i \le P_{i\max} \quad (5)$$

Ramp Rate Limits

The generator output in ELD problems is usually assumed to be adjusted smoothly and instantaneously. However, under practical circumstances ramp rate limit restricts the operating range of all the online units for adjusting the generation operation between two operating periods. The inequality constraint due to ramp rate limits[14] of i^{th} unit because of change in generation are given by the constraint

$$\text{Max}\left(P_{i\min}, P_i^0 - D_{ri}\right) \le P_i \le \text{Min}\left(P_{i\max}, P_i^0 + U_{ri}\right) \quad (6)$$

if generation increases, $P_i - P_i^0 \le U_{ri}$ (7)

if generation decreases, $P_i^0 - P_i \le D_{ri}$ (8)

Prohibited Operating Zones

The input-output characteristics of modern units are inherently non-linear because of steam valve point loadings[3]. The operating zones due to valve point loading or vibration due to shaft bearing is generally avoided in order to achieve best economy, called prohibited operating zones of a unit, makes the curve discontinuous in nature. The feasible operating zones of i^{th} unit having k number of prohibited

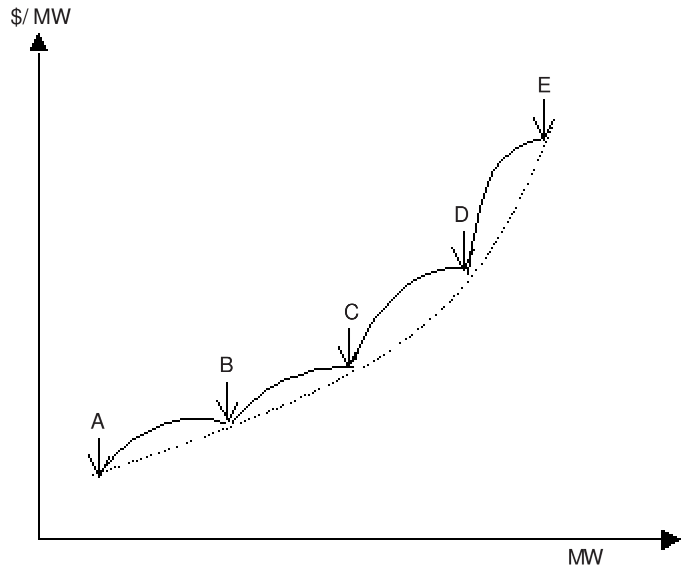

Figure 1 Example of cost function with five valves from A to E

operating zones is represented by

$$P_i \notin [P_{iL}^{pzk},\ P_{iU}^{pzk}];\ k = 1,\ 2 \ldots\ldots \quad (9)$$

$$P_i \le P_{iL}^{pzk} \text{ and } P_i \ge P_{iU}^{pzk} \quad (10)$$

Case B : Cost Function with Valve Point Effects

The generators with multiple valve steam turbines[14] possess a wide variation in the input-output characteristics as in Figure 1. Therefore the actual cost curve is a combination of sinusoidal functions and quadratic functions represented by the equation (12).

$$\text{Minimize } F = \sum_{i=1}^{m} f_i(P_i) \quad (11)$$

Subject to equation (5) and following equation.

$$f_i(P_i) = a_i + b_i P_i + c_i P_i^2 + \left| e_i \times \sin\left(f_i \times (P_{i\min} - P_i)\right)\right| \quad (12)$$

PARTICLE SWARM OPTIMIZATION

Brief Overview

The PSO idea was originally introduced by Kennedy and Eberhart[7] as an optimization technique inspired by swarm intelligence and theory in general, such as, bird flocking, fish schooling and even human social behaviour. Particles change their positions with time through search space. Each particle represents a candidate solution to the optimization problem. During flight, each particle adjusts its position according to its own experience, and the experience of neighbouring particles as a constructive cooperation, making use of the best positions encountered by itself and its neighbours.

The position mechanism of the particle in the search space is updated by adding the velocity vector to its position vector given in equation (14) and as illustrated in Figure 2.

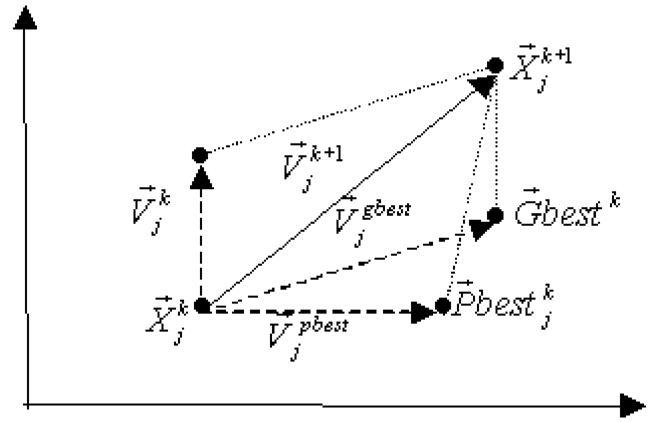

Figure 2 The search mechanism of PSO by j[th] particle

Let *X* and *V* be particle position and its corresponding velocity in a search space, respectively. The best position achieved by a particle is recorded and denoted by P_{best}. The best particle among all particles in the population is represented as G_{best}. According to Clerc, the use of constriction factor that ensures convergence of PSO algorithm[11]. The updated velocity and position of a particle can be calculated as shown in the following formulae.

$$\vec{V}_{ji}^{k+1} = K * \left(w * \vec{V}_{ji}^{k} + c_1 * rand(\ ) * \left(\vec{P}best_{ji} - \vec{X}_{ji}^{k}\right) + c_2 * rand(\ ) * \left(\vec{G}best_i - \vec{X}_{ji}^{k}\right)\right) \quad (13)$$

$$\vec{X}_{ji}^{k+1} = \vec{X}_{ji}^{k} + \vec{V}_{ji}^{k+1};\ j = 1,2,\ldots n,\ i = 1,2,\ldots m \quad (14)$$

The constriction factor can be represented as the following equation

$$K = \frac{2}{\left[2 - c - \sqrt{c^2 - 4c}\right]};\ \text{where } c = c_1 + c_2 \text{ and } c > 4 \quad (15)$$

In general the inertia weight, *w* is set according to the following equation

$$w = w_{max} - \frac{w_{max} - w_{min}}{iter_{max}} \times iter \quad (16)$$

The particle velocities V_{min}, V_{max} are limited by some maximum value. The maximum velocity is given as

$$V_{max} = (X_{max} - X_{min})/k, \text{ and } V_{min} = -V_{max} \quad (17)$$

Dynamic Search-space Squeezing Strategy

Judicious choice of search space of the particle not only improves the speed of convergence but also ensures the algorithm to be less susceptible to getting trapped on local minima, *ie*, the solution of IPSO is highly optimal. When there are no significant improvements in the performance of solution achieved, the dynamic search-space squeezing

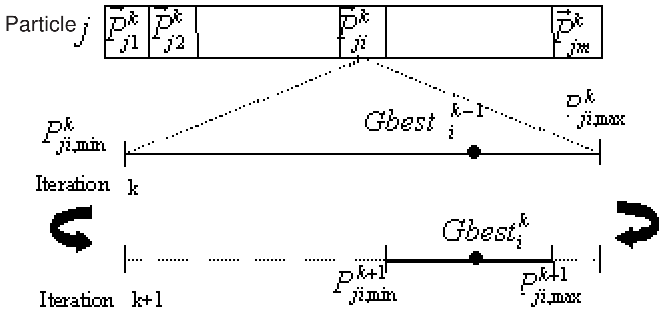

Figure 3 Depicts the search space squeezing mechanism of the j[th] particle during activation

strategy is activated. In this case, the search space is dynamically readjusted (*ie*, squeezed) based on the relative distance between G_{best} and lower and upper limits of i th generator denoted by Δ_{Li} and Δ_{Hi}, respectively. Both the relative distances are variables, not always equal and constant, which are represented as,

$$\Delta^k_{Li} = \frac{Gbest^k - P_{i,min}}{P_{i,max} - P_{i,min}}, \quad \Delta^k_{Hi} = \frac{P_{i,max} - Gbest^k}{P_{i,max} - P_{i,min}},$$

$$\Delta^k_{Li} + \Delta^k_{Hi} = 1 \qquad (18)$$

At iteration $k+1$, the adjusted limits of output of generator i are determined as follows

$$P^{k+1}_{i,min} = P_{i,min} + \left(Gbest^k_i - P_{i,min}\right) \times \Delta^k_{Li},$$

$$P^{k+1}_{i,max} = P_{i,max} - \left(P_{i,max} - Gbest^k_i\right) \times \Delta^k_{Hi}, \qquad (19)$$

The limits of output of generators are varying in every iteration but always dependent on the location of *Gbest* in the boundary. The updated maximum and minimum limits are described in equation (18) and equation (19) and always satisfied by equation (3) to equation (12).

The activation of dynamic space squeezing process is illustrated in Figure 3.

Improved PSO for ELD Problems

The computational processes of improved PSO technique can be described as follows.

(1) Initialize randomly the particles of the population. These particles must be feasible candidate solutions that satisfy all given constraints.

(2) Let $P_j = [P_1 \ P_2 .... P_m]$ be the trial vector denoting the particles of population to be evolved. The elements of P_j are the real power outputs of the committed *m* generating units subjected to their respective capacity constraints in (5).To meet exactly the load demand in (3), a dependent unit is randomly selected from among the committed m units. Let P_d be the power output of the dependent unit (slack generator), then P_d is calculated as below and satisfied by (5).The step 3 is repeated for few iterations.

$$P_d = P_D - \sum_{\substack{j=1 \\ j \neq d}}^{m} P_j \ ; \ j = 1,2,\ldots,m \qquad (20)$$

(3) Compare each particle evaluation value with its *Pbest.* The best evaluation value among the *Pbest* is denoted as *Gbest*.

(4) Update the iteration .

(5) Update inertia weight using equation (16).

(6) Update velocity and position of each particle within their assigned limits using equations (13), (14) and (17).

(7) Each particle is evaluated according to its updated position. If the evaluation value of each particle is better than the previous *Pbest*. The current value is set to be *Pbest*. If the best *Pbest* is better than *Gbest*, the value is set to be *Gbest* .

(8) If the stopping criterion is satisfied, then go to step 9. Otherwise go to step 2.

(9) The space squeezing strategy is activated to adjust the upper and lower boundaries of the particles using equation (19) for few iterations. If the performance is improving, then go to step 1 with new parameters.

(10) The particle that generates the latest *Gbest* is the optimal value.

Stopping Rule

The iterative procedure of generating new solutions with minimum function value is terminated when there are no significant improvements achieved in the solution. It can also be terminated when a predefined maximum number of iterations (generations) are reached. In the present work the

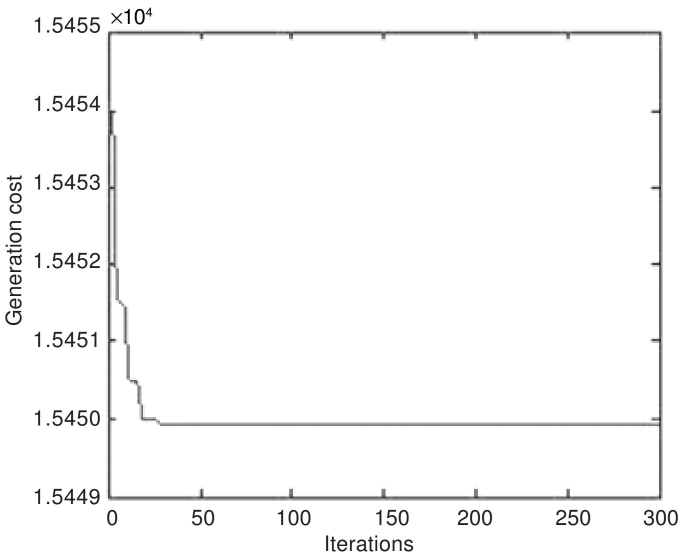

Figure 4 Convergence characteristics of six unit system by IPSO

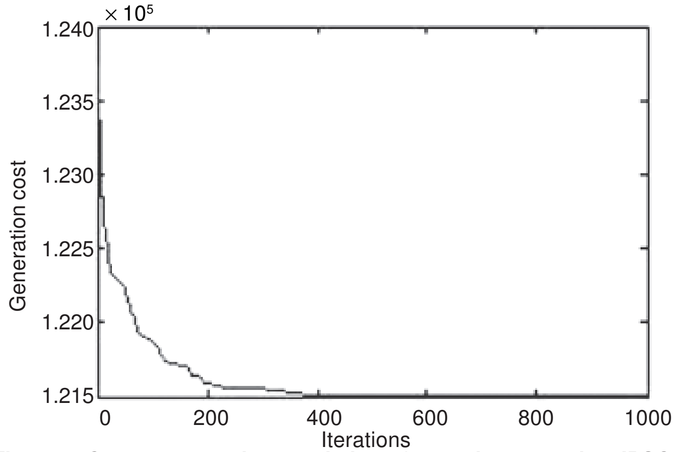

Figure 5 Convergence characteristics of 40 unit system by IPSO

former method is employed. Once terminated, the algorithm reports the values of *Gbest* and f (*Gbest)* as its solution.

RESULTS AND DISCUSSION

The present work has been implemented in command line in MATLAB 7.0 for the solution of economic load dispatch with smooth and non-smooth cost functions. After several trials with different values of PSO parameters, such as, inertia weight, number of particles, constriction factor, maximum allowable velocity. Details of key parameters selected such as, w_{max}= 0.7, w_{min}=0.1, c_1= c_2=2.05 , n =30, K = 0.7295. When dynamic search squeezing strategy is activated then, the new parameters selected as w_{max}=0.01, w_{min}=0.0, c_1= c_2 =2.0, n =30, K=0.7295.

Sample 1 : ELD with Smooth Cost Function

The program applied in two test systems, one with six generators and another with 40 generators (non-smooth). The input data for six generator system are given in Gaing[14] and those for 40 generators in Chen and Chang[6]. Here, the total demand for the 6 generator and 40 generator systems are set as 1263 MW and 10 500 MW, respectively.

The global solution for six generator system and 40 generator systems is yet to be discovered. It was reported that the best local solution for 6 generator system[16] as 15 448 $ but in which the total load demand is not fulfilled. The network losses of six generator system for the given schedule[16] should be 13.1997 MW but it was reported as 12.655 MW. Similarly the best local solution in case of 40 generator system was reported[15] as 122,252.265 $. Table 1 shows the best solution among 50 trials may not be the global solution but IPSO has shown its robustness and superiority to the existing methods[15].

Table 1 Best solution for six unit system

Unit power output, MW	**IPSO**	**AIS**	**PSO**	**GA**
P1	447.4991	458.2904	447.4970	474.8066
P2	173.3448	168.0518	173.3221	178.6363
P3	263.5037	262.5175	263.4745	262.2089
P4	139.0478	139.0604	139.0954	134.2826
P5	165.4444	178.3936	165.4761	151.9039
P6	87.1186	69.3416	87.1280	74.1812
Total power output	1275.9584	1275.655	1276. 01	1276. 03
P_{loss}, MW	12.9584	13.1997	12. 9584	13. 0217
P_D, MW	12 63. 0	1262. 5	1263. 0	1263. 0
Total generating cost, $/h	15,449.9	15,448	15,450	15,459

Table 2 Comparison of methods on relative frequency of convergence in the ranges of 40 unit system

Methods	126.5-127.0	126.0-126.5	125.5-126.0	125.0-125.5	124.5-125.0	124.0-124.5	123.5-124.0	123.0-123.5	122.5-123.0	120.0-122.5
CEP	10	4	-	16	22	42	4	2	-	-
FEP	6	-	4	2	10	20	26	24	6	-
MFEP	-	-	-	-	-	14	26	50	10	-
IFEP	-	-	2	-	4	4	18	50	22	-
MPSO	-	-		-	-	-	-	-	53	47
IPSO	-	-	-	-	-	-	-	-	15	85

Table 3 Best solution for 40 unit systems

Unit	P_{min}	P_{max}	**Generation**	**Cost**
1	36	114	112.1079	946.877
2	36	114	110.9706	927.941
3	60	120	97.3999	1190.548
4	80	190	179.7332	2143.552
5	47	97	96.9990	853.163
6	68	140	139.9999	1596.464
7	110	300	259.5999	2612.889
8	135	300	284.6021	2779.881
9	135	300	284.6009	2798.253
10	130	300	204.7998	3618.493
11	94	375	168.7998	2959.458
12	94	375	168.7998	2977.455
13	125	500	214.7598	3792.070
14	125	500	304.5196	5149.700
15	125	500	394.2794	6436.587
16	125	500	304.5196	5171.198
17	220	500	489.2794	5296.711
18	220	500	489.2794	5288.766
19	242	550	511.2794	5540.930
20	242	550	511.2794	5540.910
21	254	550	523.2794	5071.290
22	254	550	523.2794	5071.290
23	254	550	523.2794	5057.224
24	254	550	523.2794	5057.224
25	254	550	523.2794	5275.089
26	254	550	523.2795	5275.091
27	10	150	10.0180	1140.938
28	10	150	10.0010	1140.547
29	10	150	10.0043	1140.623
30	47	97	96.9833	852.934
31	60	190	190.0000	1643.991
32	60	190	189.9999	1643.991
33	60	190	190.0000	1643.991
34	90	200	164.8039	1585.615
35	90	200	164.8136	1540.105
36	90	200	164.8117	1540.073
37	25	110	109.9999	1220.166
38	25	110	109.9999	1220.166
39	25	110	109.9999	1220.166
40	242	550	511.2794	5540.930
Total generation and cost			10 500.000	1 21 503.292

Table 4 Comparison of simulation results of each method considering valve point effects of 40 unit system

Methods	Minimum cost, $
CEP	123488.29
FEP	122679.76
MFEP	122647.57
IFEP	122624.35
MPSO	12252.625
IPSO	121503.292

Sample 2 : ELD with Non-smooth Cost Function Considering Valve Point Loading Effects

The system consists of 40 generators with a load demand of 10 500 MW. To observe the robustness and superiority of IPSO has been applied and the obtained best result is compared with relative frequency of other methods[15], such as, classical evolutionary programming (CEP), fast EP (FEP), modified FEP (MEP), improved FEP (IFEP) and modified PSO (MPSO) and the solution quality of 100 trials were performed and the obtained statistical results are reported in Table 2.

The generation outputs and the corresponding costs of the best solution are provided in Table 3. The best solution provided among 100 trials, may not be the global solution but the results validating the heuristics applicability.

In Table 4, one can see the applicability and viability of the aforementioned technique from the obtained best result compared with other existing heuristics methods[15].

CONCLUSION

The paper has employed IPSO algorithm on the constrained economic load dispatch problems. The IPSO has provided the global solution satisfying the constraints for the ELD problems with smooth cost function and with non smooth cost function due to valve point effects. In both the cases IPSO has shown its superiority and better than the earlier best results. IPSO algorithm works superbly in case of large scale power systems. The IPSO method not only gives better solution in terms of minimum cost as well as transmission loss but also stable convergence characteristics and good computational efficiency.

REFERENCES

1. A J Wood and B F Wollenberg. 'Power Generation Operation and Control.' *John Willey and Sons*, New York, 1984, p 23.

2. F N Lee and A M Breiphol. 'Reserve Constrained Economic Dispatch with Prohibited Operating Zones.' *IEEE Transactions on Power System*, vol 12, February 1993, p 246.

3. K P Wong and C C Fung. 'Simulated Annealing based Economic Dispatch Algorithm.' *IEE Proceedings Part C*, vol 140, no 6, 1992, p 544.

4. D C Walters and G B Sheble. 'Genetic Algorithm Solution of Economic Dispatch with Valve Point Loading.' *IEEE Transactions on Power System*, vol 8, August 1993, p 1325.

5. A Bakirtzis, V Petridis and S Kazarlis. 'Genetic Algorithm Solution to the Economic Dispatch Problem.' *Proceedings Inst Elect Eng-Gen*, *Trans Dist*, vol 141, no 4, July 1994, p 377.

6. P H Chen and H C Chang. 'Large Scale Economic Dispatch by Genetic Algorithm.' *IEEE Transactions on Power System*, vol 10, no 4, November 1995, p 1919.

7. J Kennedy and R Eberhart. 'Particle Swarm Optimization.' *Proceedings of IEEE International Conference on Neural Networks*, vol 4, Perth, Australia, 1995, p 1942.

8. Y Shi and R C Eberhart. 'A Modified Particle Swarm Optimizer.' *Proceedings of IEEE International Conference on Evolutionary Computation*, *Anchorage*, May 1998, p 69.

9. R C Eberhart and Y Shi. 'Comparison between Genetic Algorithms and Particle Swarm Optimization.' *Proceedings of IEEE International Conference on Evolutionary Computation*, *Anchorage*, May 1998, p 611.

10. Y Shi and R C Eberhart. 'Empirical Study of Particle Swarm Optimization.' *Proceedings of Congress on Evolutionary Computation*, *Piscataway*, 1999, pp. 1945-1950.

11. R C Eberhart and Y Shi. 'Comparing Inertia Weights and Constriction Factors in Particle Swarm Optimization.' *Proceedings of Congress on Evolutionary Computation*, 2000, p 84.

12. H Yoshida, K Kawata, Y Fukuyama, S Takayama and Y Nakanishi. 'A Particle Swarm Optimization for Reactive Power and Voltage Control Considering Voltage Security Assessment.' *IEEE Transactions on Power System*, vol 15, November 2000, p 1232.

13. M A Abido. 'Optimal Design of Power System Stabilizers using Particle Swarm Optimization.' *IEEE Transactions on Energy Conversion*, vol 17, no 3, September 2002, p 406.

14. Zwe-Lee Gaing. 'Particle Swarm Optimization to Solving the Economic Dispatch Considering the Generator Constraints.' *IEEE Transactions on Power System*, vol 18, no 3, August 2003, p 1187.

15. J B Park, K S Lee, J R Shin and K Y Lee. 'A Particle Swarm Optimization for Economic Dispatch with Non-smooth Cost Functions.' *IEEE Transactions on Power System*, vol 20, no 1, February 2005, p 34.

16. B K Panigrahi, S R Yadav, S Agarwal and M K Tiwari. 'A Clonal Algorithm to Solve Economic Load Dispatch.' *Electrical Power System Research*, vol 77, 2007, p 1381.